



New Approaches to Microwave Remote Sounding of Atmospheric Composition Profiles

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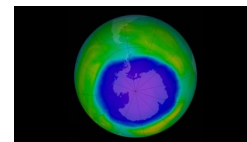
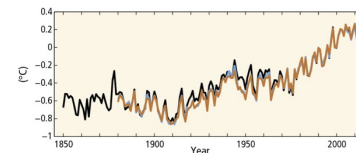
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Photograph by ISS astronaut Ron Garan



- Motivation – the need for new and continued observations of Earth's stratosphere
 - witnessed in part by the unusual behavior seen in the last three years
- The Microwave Limb Sounder on NASA's Aura mission (2004–)
- The Continuity Microwave Limb Sounder (C-MLS) instrument concept
 - New sideband-separating 340 GHz receiver
 - Dramatic advances enabled by CMOS technology (tone generators and spectrometers)
- A different measurement concept focused on a specific scientific hypothesis:
 - “Stratospheric Water Inventory – Tomography of Convective Hydration” (SWITCH)
- Summary and next steps

- We greatly need improved understanding and predictive capability for atmospheric composition
 - both on the minutes-to-weeks timescales needed for air quality forecasting
 - and on the seasonal-to-decadal timescales needed for climate forcings and feedbacks
- The poor representation of key processes in the upper troposphere and stratosphere (UTLS) in models is a significant barrier to meeting this need
 - These altitudes are where impacts of water vapor (the strongest greenhouse gas) and ozone (a strong and variable greenhouse gas) are greatest
 - The region is characterized by strong gradients and large spatial and temporal variability (e.g., from convective outflow), as well as long chemical lifetimes and strong winds that promote the long-range transport of pollutants
- Further up in the atmosphere, the stratosphere will continue to undergo severe ozone destruction so long as anthropogenic halogen levels remain high
- Furthermore, considerable but poorly understood variability in stratospheric water vapor significantly affects surface temperature and the ozone layer



The stratosphere's history of surprising us

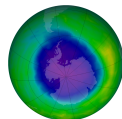


1974: Molina and Rowland show that long-lived chlorofluorocarbons (CFCs) can survive the journey to the stratosphere, where the strong sunlight breaks them down, releasing ozone-destroying chlorine. Prior to then, the prevailing wisdom was that the main threat to the ozone layer was the slow increase in N_2O from fertilizers.



1970s

1985: Farman et al. report decreases in springtime ozone over Antarctica (the so-called "ozone hole"). Prior to that discovery, the expectation had been that CFCs would slowly deplete ozone world-wide, mainly in the upper stratosphere.



1980s

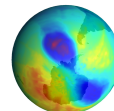
1991: Mt. Pinatubo erupts, leading to strong enhancement in stratospheric aerosol.



1990s

2000: The steady climb in stratospheric humidity during the 1980s (when routine balloon-based observations began) and 1990s ended with a sudden ~10% drop. This is estimated to have reduced surface warming in the subsequent decade by ~25%.

2002: An unprecedented "major warming" event in the Antarctic winter stratosphere results in the smallest ozone hole since the 1980s.



2000s

2011 (& 2020): For the first (and second) time, the prolonged cold conditions in the Arctic winter stratosphere result in degrees of ozone depletion typically associated with Antarctic ozone holes.

2010s

2019: An unexpected slow-down in the poleward transport of air in the northern hemisphere mid-stratosphere. A far "older" chemical signature is seen than in previous years.

2020: An unprecedented fire in Australia lofts record levels of the pollution to the lower stratosphere where it continues to rise and circulate in a coherent plume for four months.

Stay tuned for news of the implications of this event ...



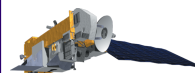
2020s

1992: UARS MLS observations show forest-fire pollution lofted to lower stratosphere following PyroCumulonimbus convection; among the earliest evidence of such transport.



1991–2000: UARS MLS

2015/2016: The Quasi Biennial Oscillation (QBO), an alternating pattern of downward-propagating easterly and westerly equatorial wind regimes with an average period of ~28 months departed from its usual periodic behavior for the first time in the ~55-year observation record.



2004–: Aura MLS



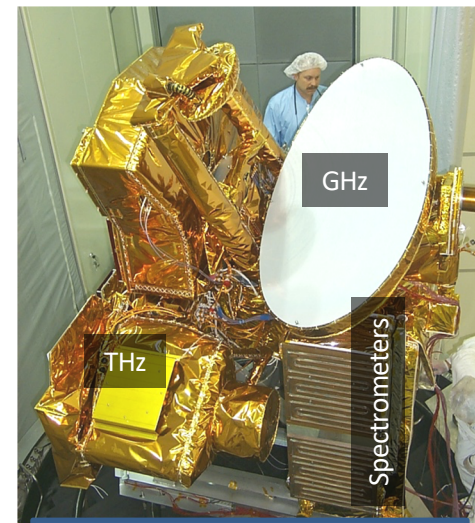
- Looking at the atmosphere edge on and scanning an instrumental field of view across the limb ($\sim 1^\circ$) yields information with good vertical resolution
 - Resolution of 1–5 km can be achieved
- The long path length associated with limb viewing provides stronger signals for the more tenuous trace gases
- However, this same path length results in coarser horizontal resolution (at least in the line-of-sight direction) than can be achieved with nadir sounders
 - “Tomographic” approaches to observation and data analysis can help redress this
- Also, atmospheric opacity limits the measurements to the region of Earth’s atmosphere above ~ 5 –10 km (lower limit varies somewhat with wavelength)
- Microwave limb sounding instruments are able to make measurements in the presence of aerosol and all but the thickest clouds

The Aura Microwave Limb Sounder (MLS)



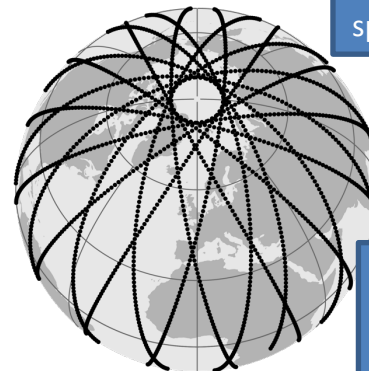
- MLS is one of four instruments launched on Aura in July 2004
- MLS measures profiles of 16 trace gases along with Temperature, geopotential height, and cloud properties
- More than 1300 papers to date use Aura MLS observations
- Currently only MLS and OMI still operate on Aura

“Should [MLS be the only Aura instrument still working], the panel finds that Aura would still be a high priority mission given the value of MLS as the most comprehensive source of stratospheric observations with high vertical resolution.” – Senior review report, 2015 (similar, though less explicit statements in 2017 and 2020 reports)



Aura MLS prior to delivery for spacecraft integration.

Receiver	Frequency	Main objectives	Aura MLS spectral bands.
R1A, R1B	118 GHz	Temperature and pressure (from O ₂)	
R2	190 GHz	Water vapor, N ₂ O, and HCN	
R3	240 GHz	O ₃ , CO, HNO ₃ , and cloud ice	
R4	640 GHz	Stratospheric halogens and radicals	
R5H, R5V	2.5 THz	Stratospheric and mesospheric OH	

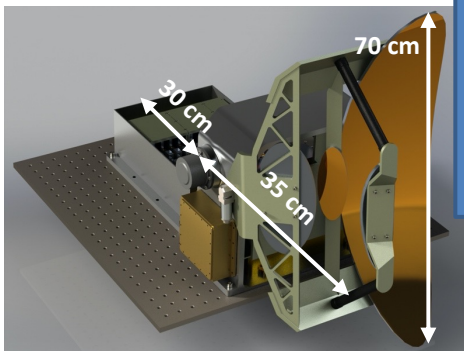


MLS observation locations for a typical day.

- Microwave instruments have historically been bulky and power hungry
- Profound innovation in the past decade, driven by the communications industry, enables dramatic reductions in mass/power/volume for most of a future MLS-like instrument, although a fairly large (70 cm to 3 m) antenna will continue to be needed
- The ESTO IIP project “Continuity MLS” started earlier this year, with the goal being to develop an Earth-Venture Common Instrument Interface compliant instrument
- Ideal for a suitable EV-Continuity call, or for the “Ozone and Trace Gas” Explorer opportunity

	Aura MLS	Continuity MLS
Measurements	O ₃ , H ₂ O, CO, HNO ₃ , N ₂ O, HCl, ClO, HOCl, BrO, HO ₂ , OH, CH ₃ CN, HCN, CH ₃ Cl, CH ₃ OH, SO ₂ , T, GPH, IWC, IWP	O ₃ , H ₂ O, CO, HNO ₃ , N ₂ O, HCl, ClO, HOCl, BrO, HO ₂ , OH , CH ₃ CN, HCN, CH ₃ Cl, CH ₃ OH, SO ₂ , T, GPH, IWC, IWP + H ₂ CO and others TBD
Resources	500 kg, 500 W 1.6m primary antenna with ~1 m ³ electronics	EV-I CII (<100 kg, <100 W) envelope – estimate 45 kg / 45 W 70 cm antenna with ~0.05 m ³ electronics
Receivers	118, 190, 240, and 640 GHz, 2.5 THz	340 and 640 GHz
Sidebands	118 GHz single sideband, all others folded sideband	Sideband separating 340 GHz, folded sideband 640 GHz
IF processing	~40 local oscillators, 60+ IF mixers, hundreds of amplifiers, attenuators and splitters	Two local oscillators, 3 IF mixers, Ten amplifier/attenuator paths
Spectrometers	542 individual channels; 4 narrow digital spectrometers	Ten 3-GHz wideband CMOS digital spectrometers

C-MLS instrument overview

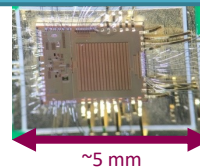


Left: Preliminary sketch of C-MLS (some optics expected to get smaller)

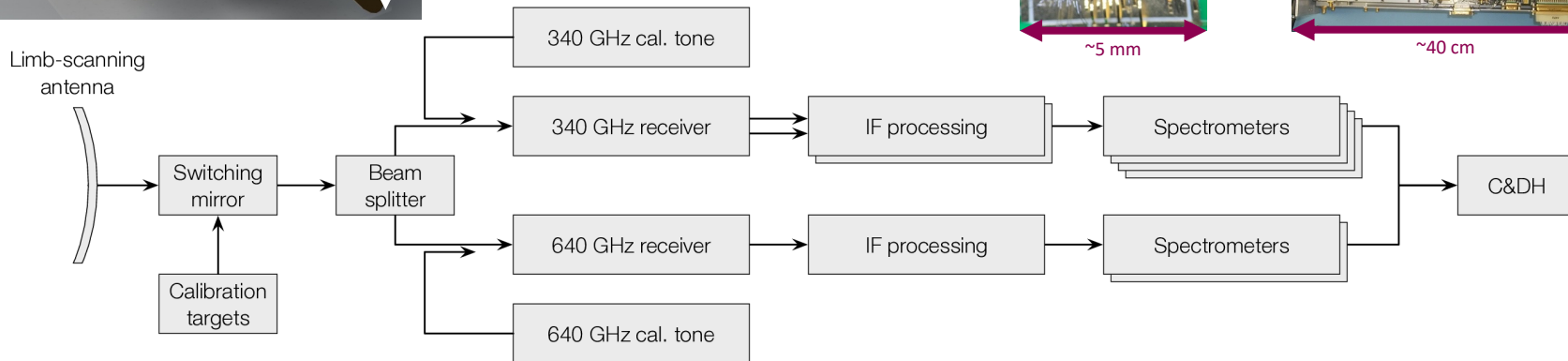
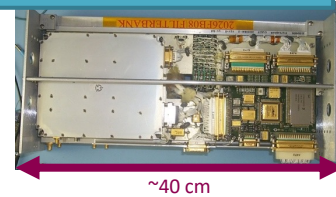
Right: Comparison of C-MLS and Aura MLS spectrometer technology

Below: High level C-MLS block diagram

C-MLS: A 4096-channel 3-GHz spectrometer on ~5 mm chip. Overall PCB is ~credit-card-sized.

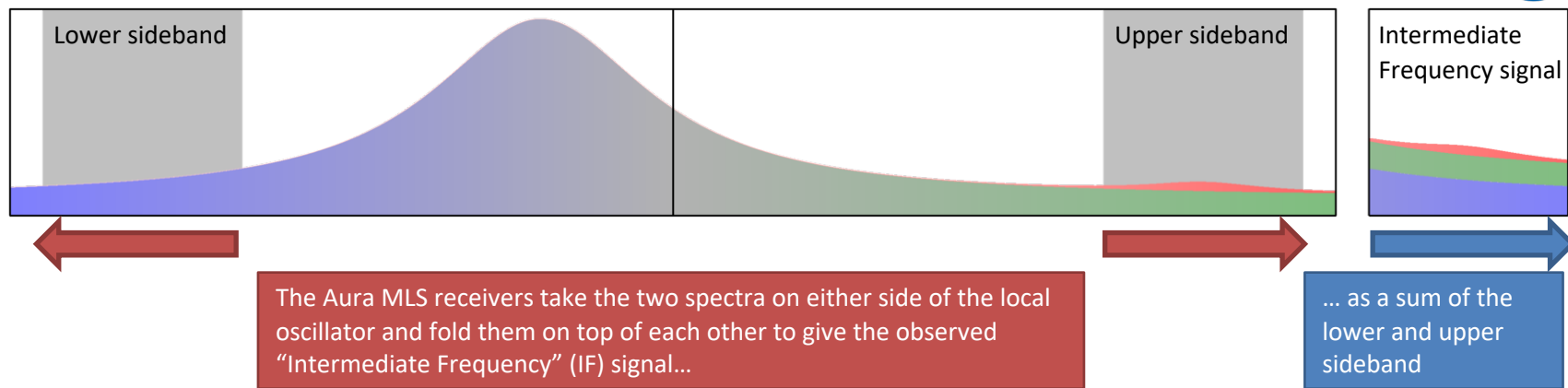


Aura MLS: A 25-channel ~1.5-GHz spectrometer from Aura MLS, ~1.5 kg, ~40 cm.



- The block diagram resembles that of many previous microwave spectrometers (including Aura MLS)
- We have introduced additional oscillators to provide additional in-space calibration capability
- Newly developed tunable CMOS W-band tone generators are key to these, and to the receiver Local Oscillators
- The CMOS 3 GHz digital spectrometer offers huge reduction in back end complexity and power consumption

Consequences of using “folded sideband” measurements

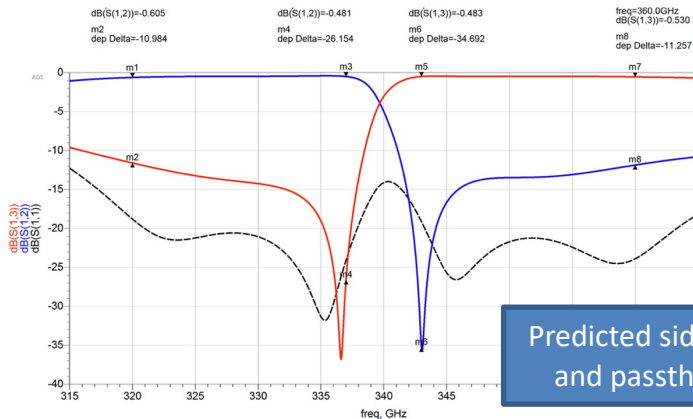
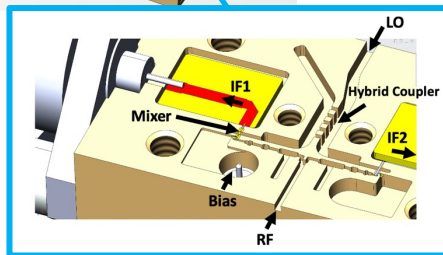
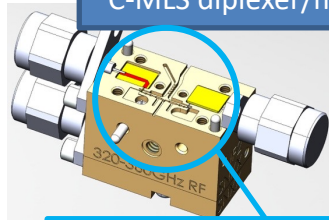


- The “folded sideband” nature of the Aura MLS signals presents a significant challenge to measurements in the upper troposphere and lower stratosphere
- The far-wing/continuum signal in the upper sideband (green) adds a “baseline” but also partially attenuates the weak spectral signal from the target molecule (red)
- The far-wing/continuum signal in the lower sideband (blue) simply adds more baseline
- Deducing the abundance of the “red” molecule from the total signal, given the two differently behaving background signals, equates to pulling three unknowns (red line and two continua) from only two measurements (“line shape” and “background”)
- **C-MLS solves this by reporting upper and lower sideband 340 GHz signals separately**

C-MLS 340 GHz diplexer block design

- C-MLS accomplishes the sideband separation using a “diplexer”
- One block contains two mixers (LSB, USB) and the splitter/filter waveguide structures for separating the two signals

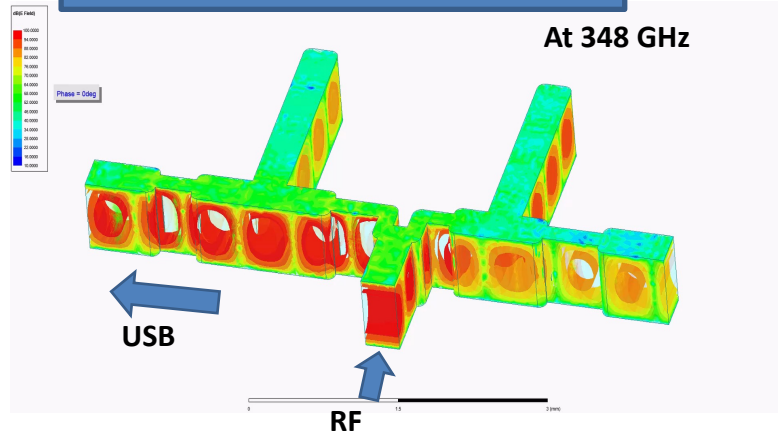
C-MLS diplexer/mixer block.



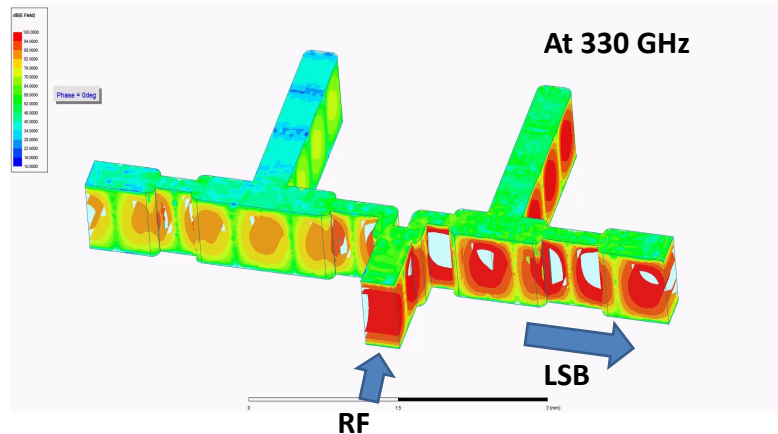
Predicted sideband rejection and passthrough factors.

Propagation of waves above (upper) and below (lower) the center frequency.

At 348 GHz



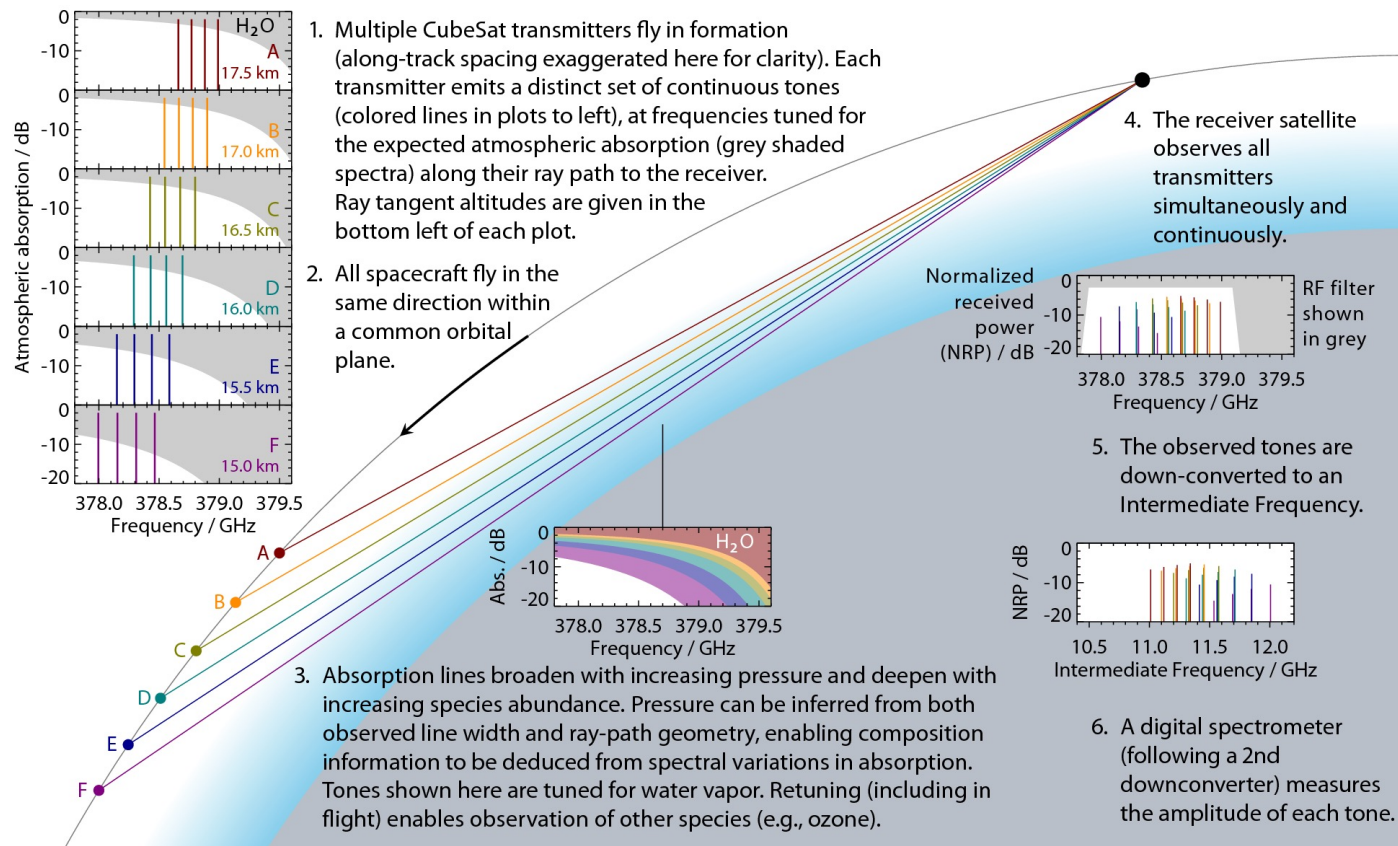
At 330 GHz



Stratospheric Water Inventory – Tomography of Convective Hydration (SWITCH)



(an active microwave limb sounding approach for high vertical resolution water vapor measurements)



The SWITCH mission concept targets high vertical (~500 m) and along-track (~10 km) resolution observations of water vapor.

The SWITCH science objective is to quantify the degree to which water vapor plumes injected into the lower stratosphere by deep convection hydrate the stratosphere globally, leading to a positive climate feedback.

C-MLS inherits tone generator technology from SWITCH.



- Despite a nearly 16-year record from MLS (and the earlier record from past sensors), the middle atmosphere has not lost its capacity to surprise us and/or exhibit envelope-redefining behavior
- There is an urgent need for a low-cost approach to continuing widely used observations of Earth's upper troposphere, stratosphere, and mesosphere from instruments like Aura MLS
 - Very few instruments making such measurements remain, most around two decades old. Of these, Aura MLS is arguably the most widely used
 - Prospects for future missions/instruments to continue these observations are meagre
- The “Continuity Microwave Limb Sounder” (C-MLS) concept can meet this need
- New technology enables significant reductions in mass and power
 - C-MLS is estimated at 45 kg, 45 W vs. 500 kg, 500 W for Aura MLS
- We are very grateful to ESTO for their support of C-MLS, SWITCH, and prior projects
- We also greatly appreciate support from NASA ESD for the “Airborne Scanning Microwave Limb Sounder” (A-SMLS) and, of course, for their continued support of Aura MLS